

2

AD-A216 921

THE INDEX OF HARM: A MEASURE FOR COMPARING
OCCUPATIONAL RISK ACROSS INDUSTRIES

DTIC
ELECTE
JAN 19 1990
S D CS D

Kenneth A. Solomon
Kirsten A. Alesch

March 1988

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

P-7405

90 01 16 014

The RAND Corporation

Papers are issued by The RAND Corporation as a service to its professional staff. Their purpose is to facilitate the exchange of ideas among those who share the author's research interests; Papers are not reports prepared in fulfillment of RAND's contracts or grants. Views expressed in a Paper are the author's own and are not necessarily shared by RAND or its research sponsors.

The RAND Corporation, 1700 Main Street, P.O. Box 2138, Santa Monica, CA 90406-2138

ABSTRACT

This paper presents an index of harm methodology that compares occupational risk among workers exposed to radiological and nonradiological harms. It extends the work of the International Commission on Radiological Protection (ICRP) by considering American rather than European and Japanese industry groups, by treating the relative importance of various occupational harms as a parameter rather than an arbitrary constant, and by identifying several ways in which both the methodology and the database could be improved. In the analysis, we examine the risk affects of six occupational harms—three nonradiological (death, accidental injury, and disease or illness) and three radiological (somatic effects, genetic effects, and somatic effects to the fetuses or embryos of pregnant women). We performed our analysis under five different assumptions about the relative importance of averting of the six harms in question. The results of this analysis show that radiological workers exposed to the current industry average of 0.35 rem/yr are among the safest of all industry groupings, and the riskiest industries appear to be mining; agriculture, fishing, and farming; construction; transportation; and manufacturing, roughly in that order.



Accession For	
NTIS CRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By <i>lth on file</i>	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

CONTENTS

ABSTRACT	iii
FIGURES	vii
TABLES	ix
Section	
I. INTRODUCTION	1
II. ESTIMATING AN INDEX OF HARM	5
Theory and Data Assumptions	5
Nonradiological Harms	7
Radiological Harms	12
III. RESULTS AND CONCLUSIONS	17
Results	17
Conclusions	19
IV. AN ILLUSTRATIVE EXAMPLE	25
V. TOPICS FOR FURTHER RESEARCH	34
VI. REFERENCES	37

FIGURES

1. Average employment by industry for calendar years 1975 through 1985	8
2. Person-years lost per hundred person-years by nonradiological industry, in one year of occupational exposure, X_{ij} , by type of harm means for the period 1972-1985	10
3. Assumptions and weights for each type of harm	11
4. Person-years lost per 100 person-years during one year of occupational exposure, X_{ij} , by type of radiation-induced effect	15
5. Index-of-harm industry rankings for each of five assumptions ICRP reference case: nuclear fatality rates corresponding to the lowest risk model proposed in BEIR II	20
6. Indexes of harm for nonradiological industries compared with index-of-harm ranges for radiological industry by dose level, under equal weighting assumption	21
7. Average individual collective doses for 10CFR licensees 1973-1975	28
8. Reduction in index of harm through lowering the exposure limit from 5.0 to 0.5 rem/yr	31

TABLES

1. Types of harm	7
2. Indexes of harm for radiological and nonradiological industries under selected assumptions	18

I. INTRODUCTION

The adequate protection of occupational workers--and of the general population from hazards of all kinds is a concern to the federal government and many public and private organizations, as well as their counterparts in other countries. Many occupational hazards produce indeterminate effects, often disproportionately affecting some groups of individuals more than others. Determining the harm done, if it is possible to do so at all, may require time-consuming and expensive scientific studies and experimentation, without any assurance that the results will be either comprehensive or generally accepted. Moreover, many such investigations cannot be generalized to other populations, hazards, or industries.

Thus, it is only slowly that useful, incremental information is added to the general body of knowledge about occupational risk and safety. As more is known and accepted generally, so also are standards and regulations formulated and enacted. As exposure hazards increase and techniques are developed to comply with prevailing standards, those standards then tend to become progressively stricter. It may be fair to describe the present situation as a dynamic balance among the following forces:

- Value judgments about the societal benefits of materials and processes.
- Value judgments that stricter standards increase worker and general-population safety.
- Legal and administrative decisions.
- Rising costs of compliance.
- Changing occupational risk and exposure through both inexorable increases in industrial production and innovative products, materials and processes.

In past years, most health and safety standards for both general-population and occupational exposure have been formulated and classified by industry. Only recently has some thought been given to occupational risk compared across industries. Such a comparison has been attempted in ICRP Publication 27 (Ref. 1). By estimating the working time lost per worker per year from a variety of causes (accidents, disease contracted from industrial exposure, or death from occupational causes), the study reduces the harmful effects from different causes in different industries to a common denominator called an index of harm, facilitating comparisons among industries. But accurate numbers are difficult to obtain, and combining them for the comparisons is difficult to do objectively. The results of that study are generally regarded as no more than indicative of broad differences in risk among industries.

Such an analysis becomes even more complicated when the effects of radiological and nonradiological harms are compared. In addressing this comparison, ICRP Publication 27 reviewed the problems in developing its index of harm and pointed out the severe limitations inherent in both the data and the index. The comparison of radiological and nonradiological effects is complicated by the fact that low-level radiological effects consist almost entirely of delayed effects (in the commercial nuclear power industry, for example, exposures intense enough to cause immediate damage are quite rare), while the nonradiological harms consist mainly of immediate effects (precise data for delayed effects, such as cancer from nonradiological carcinogens, are virtually nonexistent because of the inherently long latency period). These effects are not totally separable, unfortunately, since very large radiation doses can lead to immediate health effects, while many nonradiological harms can result in delayed health effects (e.g., asbestosis or cancer from asbestos exposure, pneumoconiosis from coal mining, etc.). Nevertheless, in our opinion, such shortcomings do not negate the concept of using an index of harm to compare occupational risk across industries.

This study in fact extends the methodology, scope of application, and analysis of the ICRP study. Rather than calculate indexes of harm for Japanese and European industry groups, we calculate them for each of the standard eight American industry classifications (Refs. 2, 3, 4, and 5):

- Agriculture, forestry and fisheries (AF&F)
- Mining
- Construction
- Transportation
- Trade
- Finance
- Services
- Manufacturing

In addition, by combining the radiological portions of each of these industry groupings into a ninth "industry" (i.e., including only those workers in each industry exposed to any degree of radiation), we can calculate indexes of harm for the "radiological" industry for comparison.

The difficulties in estimating radiological risks to health are now widely appreciated. The conversion of this risk to years of life-shortening requires further calculations based on actuarial life tables, and an appropriate occupational-age distribution. We have not made these calculations but have relied on the rough estimates given in ICRP 27 that each premature cancer and leukemia death due to radiation results in 15 years of life-shortening. Other published estimates, based on more detailed calculations, suggest that the range of average life-shortening is between 13 and 25 years, depending on the age distribution of nuclear workers. Surprisingly, specific data on life-shortening due to fatalities are not readily available for nonnuclear industries either, except for selected subgroups. Therefore, we have used the estimate given in ICRP 27, 30 years, as the average life-shortening due to nonnuclear fatalities.

The uncertainty in life-shortening cannot be easily estimated. For occupational groups at high risk, an uncertainty of ± 20 percent in this parameter leads to an uncertainty of ± 15 percent in the index of harm. We are currently sharpening these estimates, using recent data on age at death for California occupational fatalities by industry.

Rather than selecting arbitrary, constant values to rank the importance of the various harms considered, as the ICRP study did, this study treats the issue of relative importance parametrically. It has been shown that the perception of risk depends not only on scientific evidence but on many factors, including individual and group estimates of its relative seriousness, the nature of the risk, the degree of control one has over the risk, and the relative age of and familiarity with the technologies posing the risk (Refs. 6, 7). Until we know more about how different groups and society as a whole assess risk, we must create a methodology that allows different assumptions to be tested and different weights to be assigned to each harm considered. In this way, we can stretch the value of the limited and imprecise database.

In this study, the index of harm is qualitatively defined as a measure that reflects the number of person-years lost per hundred person-years of exposure to occupationally induced injury, illness or disease, and death. The simple expressions used to calculate the index for both radiological and nonradiological industries, and under different valuations of the relative importance of different occupational harms, are discussed in Sec. II along with the data and their sources. The results and conclusions of the analysis are presented in Sec. III. In Sec. IV, we give an illustrative example of one area in which the concept of an index of harm might prove useful—the policy decision of whether the current maximum exposure dose of 5.0 rem/yr in the radiological "industry" should be lowered. That example, as well as the methodological work reported earlier, confirms how much more work needs to be done before an adequate degree of confidence can be placed in an index of harm. Accordingly, in Sec. V we offer a minimal list of topics that merit further research.

II. ESTIMATING AN INDEX OF HARM

Workers in a variety of industries are exposed to risks from a number of sources or hazards, including manufacturing processes, environmental pollutants, chemicals, and radiation. These can result in injury, illness, disease, and death. Linking cause and effect in and among industries so as to measure comparative risks is a complex task. Limited both by insufficient data and by the difficulty of weighting the relative aversions to various risks and their effects, this study nevertheless compares nonradiological with radiological occupational risks by using an index-of-harm measure.

In this section, we explain how we computed the index of harm, what simplifying assumptions had to be made, and the data we used for estimating the index for both nonradiological and radiological harms. Ideally, the index should be supported by precise data for nonradiological industries and a credible model for radiological industries. This is not yet the case. The major contribution to nonnuclear risk is from accidental fatalities. The industry-specific fatality rates are known, but for our illustrative purposes, we have only estimates about the age of accident victims. The situation is much fuzzier for nuclear-risk estimates, since the ICRP model appears to correspond to the low end of the 1972 Committee on Biological Effects of Ionizing Radiation (BEIR) risk scale.

THEORY AND DATA ASSUMPTIONS

The index of harm is an empirically derived measure of occupational risk in an industry. Although reducing everything that risk entails to a single index is presumptuous and imprecise at best, the benefits of comparing risk across industries and using the measure to reduce it selectively would seem to override that methodological naivete'. Moreover, it is only by developing such a measure that its imperfections can be revealed and steps be taken to remedy them (such as improving data availability).

The different kinds of harm and their effects encountered in the occupational environment are perceived, and hence valued, differently by both technologists and laymen.¹ Therefore, instead of trying to rank-order the harms in some way, we have concentrated on one common effect they produce—days lost from work. In the case of premature death, we calculate lost days using the mean life expectancy (for men or women, as appropriate); in other cases, we look at data for days lost from work. Reducing harm to the common denominator of days lost from work does not preclude making value choices regarding the events that cause such work and life loss; the problem's complexity is not so easily handled.

The index of harm in this paper is a function of X_i , the fraction of years lost in industry i from any cause or event by a population exposed to those causes or events for a period of 1 year. (We assume a year has 250 working days.) We also assume that the harm contributed by each major occupational cause is additive when measured in terms of lost work time. We can thus write:

$$I(X_i) = \sum_{j=1}^6 I(X_{ij}) \quad (1)$$

$$= \sum_{j=1}^6 A_{kj} N_{ij} X_{ij}, \quad (2)$$

where A_{kj} = a weighting factor that reflects the k th assumption (from a set of 5) about the relative importance of lost days from work from the j th harm (the 6 harms and 5 assumptions are discussed below); n_{ij} = the proportion of the occupational population in the i th industry exposed to the j th harm; and X_{ij} = the number of person-years lost per hundred

¹For example, it has been shown that different kinds of risk are valued differently. In a preliminary study exploring the nature of risk, the least desirable type of risk was found to be exposure to radiation, followed in order by exposure to toxic chemicals, fire, drowning, and finally accidental physical injury (Refs. 6, 7).

people in the i th industry from the j th harm during one-year (250 workday) exposure.

Because the method of calculating $I(X_i)$ is different for radiological and nonradiological harms (the populations exposed to each type are different), the remainder of this section is divided into two parts. The first part shows how we evaluate equation (2) for nonradiological harms; the second part, for radiological harms.

NONRADIOLOGICAL HARMS

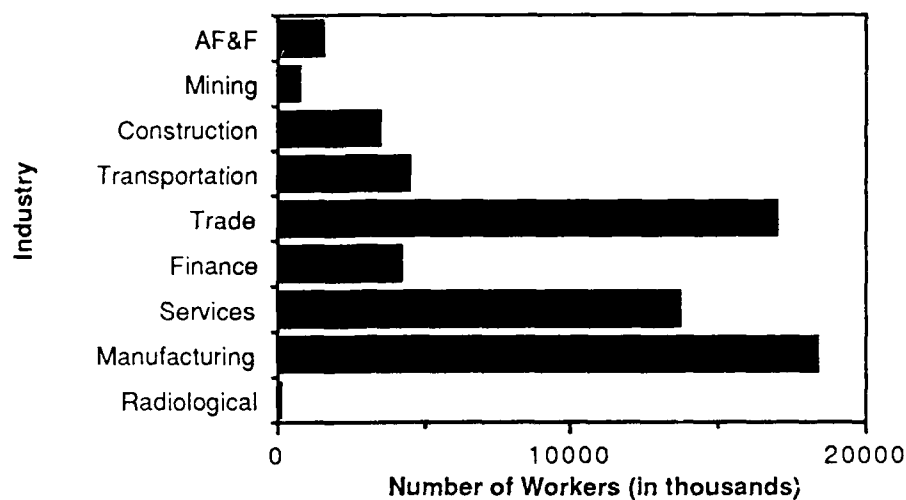
Workers in all eight American industry classifications are susceptible to the three principal nonradiological harms considered in this study—fatality, accidental injury, and illness or disease. (Table 1 lists all the harms considered.) We assume the average 1972 through 1985 employment in those industry classifications is an adequate representation of the numbers of workers exposed to those harms, and consequently we have used those figures in the analysis (both the average employment data and industry classifications are given in Figure 1).

Table 1

TYPES OF HARM

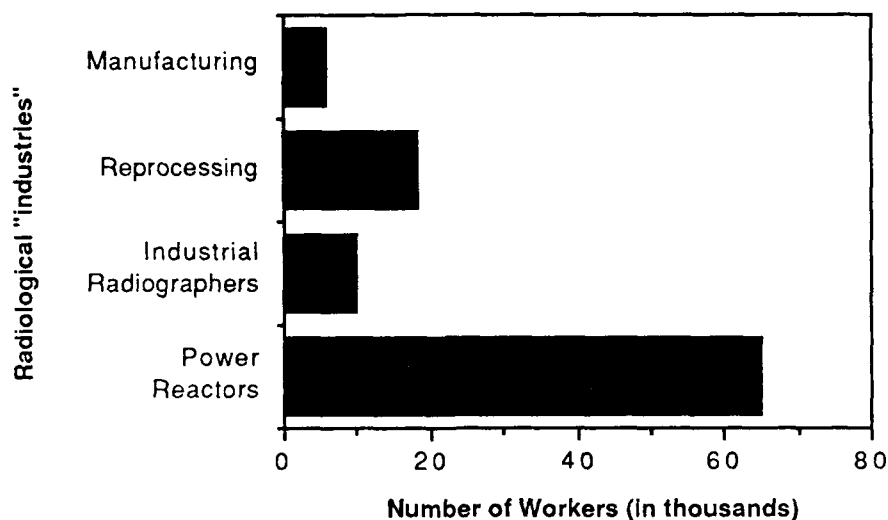
Harm Index (j)	Type of Harm
Nonradiological	
1	Fatality
2	Accidental injury
3	Occupational illness or disease
Radiological	
4	Somatic effects of radiation
5	Genetic effects of radiation
6	Somatic effects of radiation to fetuses or embryos of pregnant women

Figure 1. Average employment by industry for calendar years 1975 through 1985



Detail of Radiological Industries

^a



Source: References 2, 3, 4, 6, 7, 8, 9, 10, 11

^aExcluding medical applications, where patient exposure is voluntary and primarily beneficial, and cosmic radiation received by airline pilots and frequent air travelers.

The data on conventional nonradiological fatalities, injuries, and illness have been obtained from Refs. 2, 3, 4, 5, 8, 9, 10, and 11, and are summarized in Figures 2A, 2B, and 2C. We assume that each fatality leads to an average of 30 years of life-shortening. This is the figure suggested in ICRP 27. Accidental death rates appear to be well-documented, but the uncertainty of life-shortening suggests that at best, one-significant-figure accuracy for $j = 1$ is warranted. In addition, average values over the period 1982-1985 have been used.² These form the X_{ij} component of the index for harms 1-3 and industries 1-8.

Because all workers in these industries are exposed to these three basic harms, but not to the same degree, it is difficult to compute values for n_{ij} . However, assuming a value of one for these industries and harms is reasonable and well within the accuracy of this first-cut evaluation.

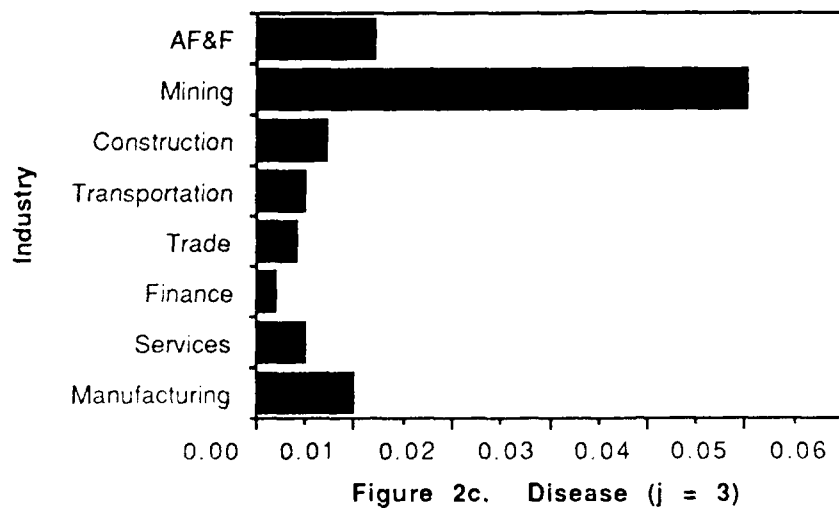
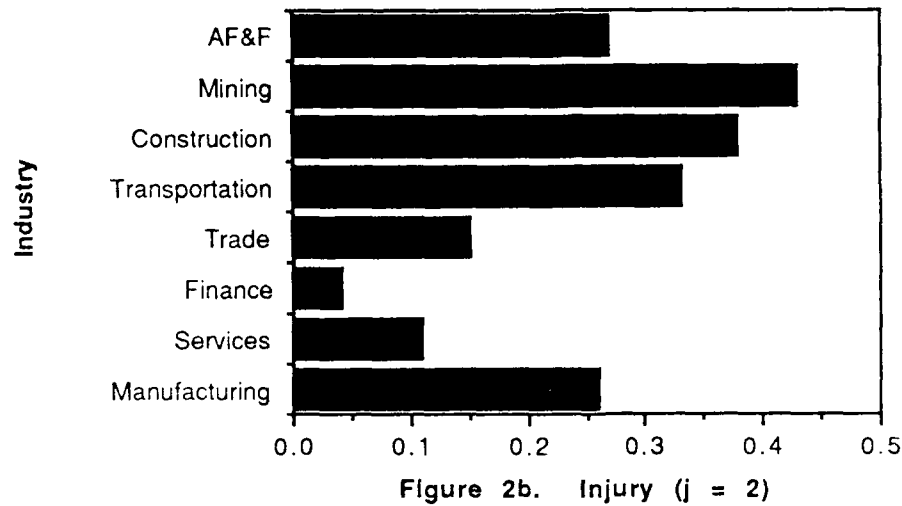
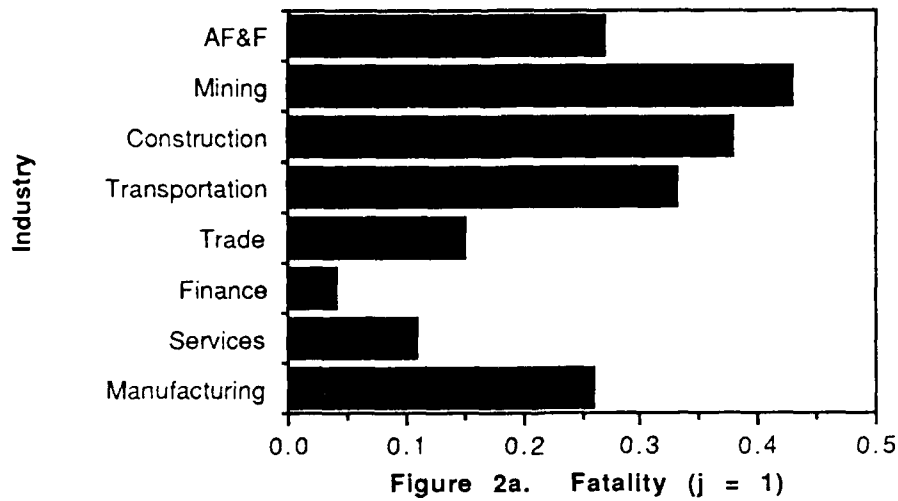
The purpose of assigning arbitrary values to the weighting variable a_{kj} was to give us some flexibility in valuing various harms. Because we wanted to test assumptions involving all six harms, we assigned values among all six "components" such that:

$$A_k = \sum_{j=1}^6 A_{kj} = 1 \quad (3)$$

for each assumption $k = 1, 5$. Figure 3 summarizes both the assumptions and values assigned to each a_{kj} . The assumptions themselves were derived from concerns expressed in the literature and by colleagues. Assumption 1 weights each harm equally and acts as a reference case. In each of the remaining four assumptions, a specific harm has been singled out for emphasis and has been arbitrarily weighted ten times more heavily than the others. For example, for $k = 3$, death ($j = 1$ and 4)

²In this preliminary analysis, we have not taken into account the potentially large interindustry variations these averages may mask.

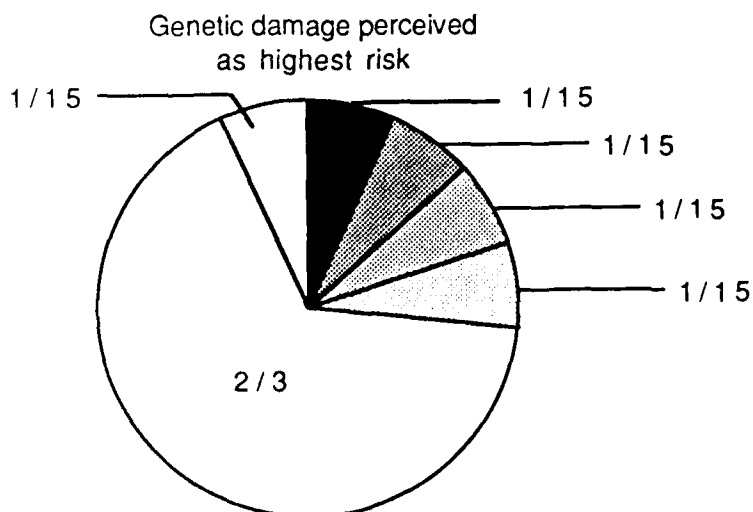
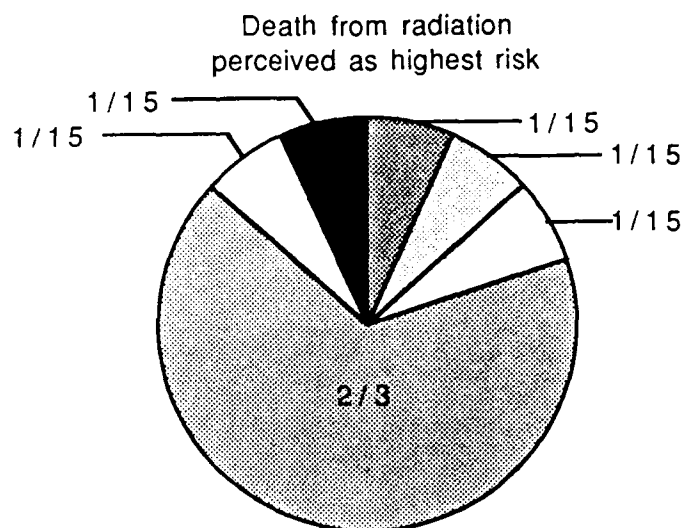
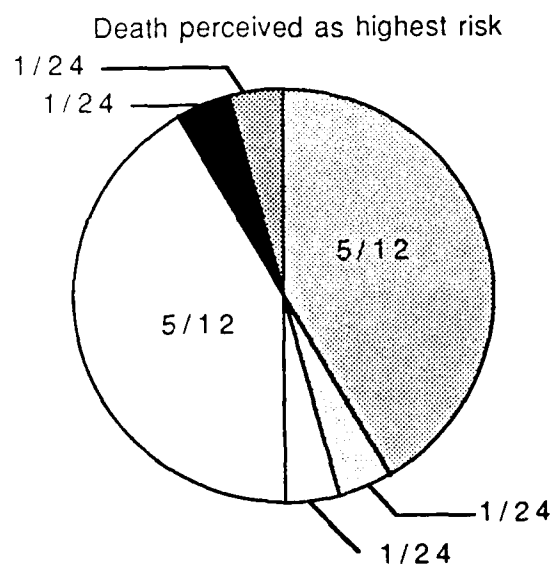
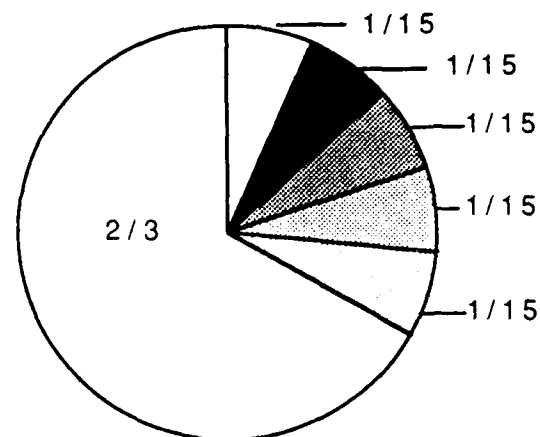
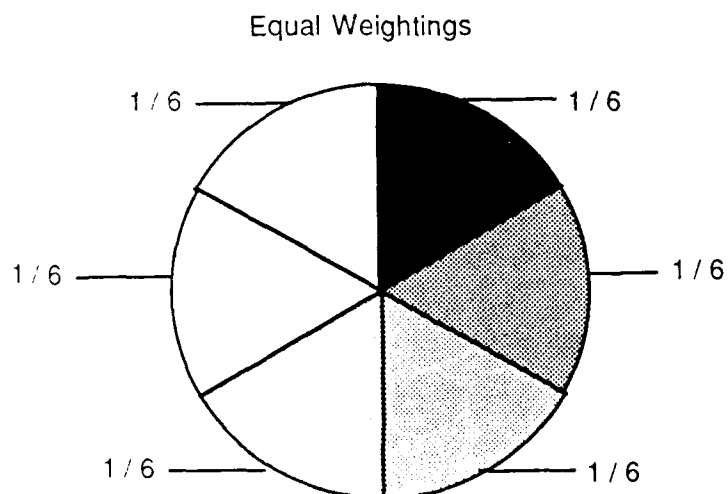
Figure 2. Person-years lost per hundred person-years by nonradiological industry, in one year of occupational exposure, X_{ij} , by type of harm means for the period 1972-1985



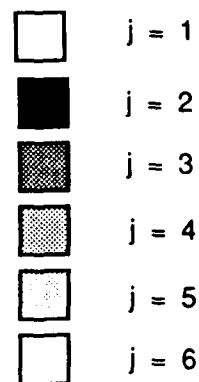
Source: References 2, 3, 4, 8, 9, 10, 11

Figure 3. Assumptions and weights for each type of harm

Radiation damage to fetuses and embryos
of pregnant women
perceived as highest risk^a



Assessed Values for Weighting
Factor a_{kj} by Type of Harm j



^a Affects all women of
child-bearing age.

was singled out; for $k = 4$ the emphasis was only on death by radiation ($j = 4$). Treating the assumptions parametrically in this way allows us to account for the variations in aversion that different individuals and groups may have toward the harm. Our formulation would permit others to experiment with different harms and still other assumptions. For example, values for A_{kj} for each assumption need not sum to unity; furthermore, the harm singled out for emphasis could be weighted by a value other than ten. Although the cases and values we have chosen for this report are arbitrary, they do illustrate the use of the methodology and hence serve our purpose.

RADIOLOGICAL HARMS

Risk from exposure to radiation increases with the radiation dose, measured in rem/yr. For this reason, we treat the dose parametrically, choosing reference values of specific significance:

Radiation dose (rem/yr)	Significance
5.0	Currently permissible ³
0.5	Proposed permissible
0.35	Current average of all workers exposed to radiation
0.25	Expected proposed average
0.1	Expected low-level average

³In the United States, the National Commission on Radiological Protection (NCRP) proposes exposure standards, often in conjunction with other groups such as the ICRP and the United Nations Scientific Committee on the effects of Atomic Radiation (UNSCEAR). The NCRP's 1949 report recognized for the first time that radiation protection criteria depended not only on biomedical and physical factors but also on value judgments. As the genetic effects of radiation became better understood, the NCRP lowered the maximum permissible dose equivalent in 1957, with which compliance was then technically feasible. At about this time, various governmental agencies began to incorporate NCRP recommendations as standards in codes and regulations. In 1972, both UNSCEAR and the Committee on Biological Effects of Ionizing Radiation (BEIR) of the National Academy of Sciences issued reports presenting for

The figure of 0.35 rem/yr--the current average dose of all workers exposed to radiation--is derived from the data in Fig. 8. There, the average individual doses lie between 0.23 and 0.40 but are skewed toward the high end of the range. The figure of 0.25 rem/yr as the expected proposed average is our own estimate, given no data on the distribution of doses under a reduced limit. However, if dropping the allowable limit from 5.0 to 0.5 rem/yr has even a small effect, we assert that the average industry dose could be reduced by perhaps 0.2 rem/yr.

This analysis treats three kinds of radiological harms: somatic effects of radiation, its genetic effects, and its somatic effects on the fetuses or embryos of pregnant women (see Table 1). Clearly, the populations exposed to these harms are only those exposed to any kind of radiation (excluding medical applications), and such workers are found in all eight industry classifications. However, the numbers of any such people are a minute fraction of the occupational work force--about 100,000 persons susceptible to radiological exposure in 1985 out of about 65 to 70 million workers (see Fig. 1).

Unfortunately, there are no empirical data available on the effects of these radiological harms on this exposed population (as noted earlier, low-level radiation produces principally delayed effects, making such data collection extremely difficult and, in the short run, impossible). Our strategy in forming a comparison of available ICRP/BEIR models with the empirical effects of nonradiological harms was simply to apply the methodology to radiological harms. To take into account the accompanying uncertainty in the estimates, we have performed a simple sensitivity analysis on those data; the results are described below.

the first time risk estimates for radiation carcinogenesis and radiation-induced genetic effects in human beings, followed in 1977 by ICRP Publication 27 with its innovative but limited index-of-harm concept.

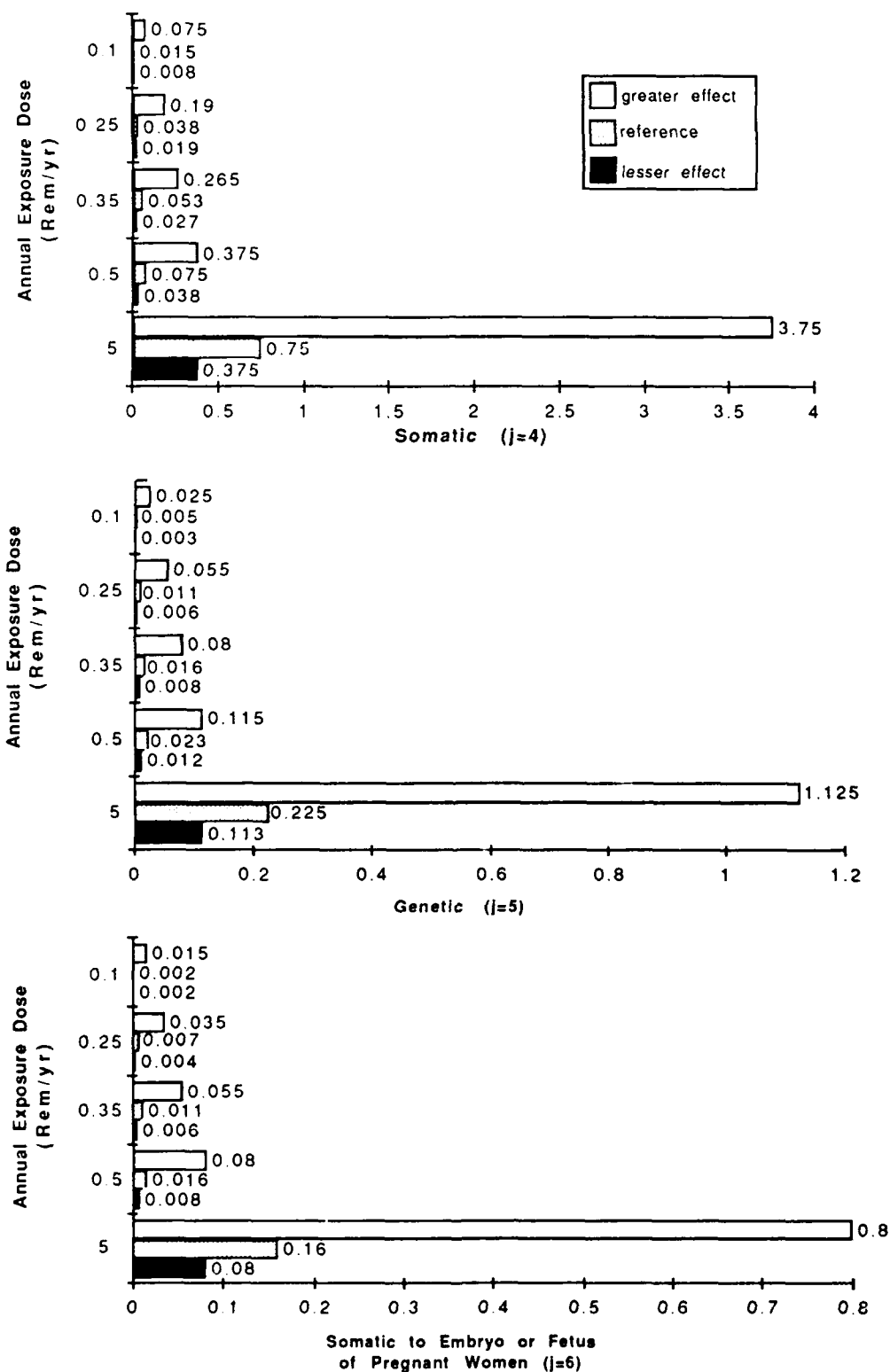
It should also be noted that the 5.0 rem/yr shown in the radiation-dose table is not the actual maximum annual dose (currently 12 rem/yr) but the average annual dose spread over a worker's lifetime after age 18. For simplicity in record-keeping, the Nuclear Regulatory Commission allows 5.0 rem/yr to be used instead.

The data we have used for estimating the effects of the radiological harms have been normalized from the ICRP study, Ref. 1, to denote the person-years lost per 100 person-years for one year of occupational exposure. We show the normalized data as the "reference" case for each effect in Fig. 4; in adjacent columns, labeled "lesser effect" and "greater effect," we have multiplied the figures in the reference column by 0.5 and 5.0, respectively. In this way, we can begin to judge the effect of viewing the accuracy of the ICRP parameters optimistically or pessimistically. The reference ICRP estimate is based on multiplying an estimated death rate of 10^{-4} per rem by 15 years of life-shortening. This value of 10^{-4} appears to correspond to the lowest estimated rate that can be made using BEIR parameters (absolute risk model, with plateau). The upper-bound estimate could be a factor of 2 or 3 times this figure.

The data for radiation-induced somatic effects reflect only their stochastic or random component. (Nonstochastic or "linear" effects, which can occur only on exposure to doses above some threshold, say 25 rem/yr, are unlikely to be a factor within present allowable limits, and thus are ignored.) Stochastic effects can raise the incidence of cancers in people exposed to low-level radiation and could result in premature death.

Radiation-induced genetic damage is distinguished from teratogenic effects in that the former applies to both men and women. Either of whom could pass genes and chromosomes damaged by radiation to their offspring. The latter applies only to fertile women, especially pregnant women, and affects the ova, embryos or fetuses directly. Thus, the latter type of damage is somatic in nature; the former genetic. Radiation damage to fertile women may, if severe enough, prevent the development or implantation of the fertilized ovum, cause abortion of a nonviable fetus, or result in a liveborn child with genetic abnormalities. Because of lack of data, however, calculation of the harm resulting from both types of damage depends critically on subjective judgment. For example, we do not know to what extent second- and third-generation offspring are affected by genetic, embryotic, or

Figure 4. Person-years lost per 100 person-years during one year of occupational exposure, X_{ij} , by type of radiation-induced effect



Source: Extrapolated from References 6 and 7.

fetal damage, especially when more than one damaged offspring may result.

The numbers in Fig. 4 are all we have as proxies in this highly uncertain area. Somatic stochastic effects seem to have the potential for more harm than the other two kinds added together, although our simplistic measurement of harm does leave out many important considerations.

III. RESULTS AND CONCLUSIONS

RESULTS

Table 2 and Fig. 5 together present the computed indexes of harm under the five different weighting assumptions for both radiological and nonradiological industries using the Reference ICRP dose/risk model. Table 2 shows the results numerically; the figure depicts the industry rankings graphically by individual assumption as defined in Fig. 3. We point out again that the ICRP fatality rate appears to correspond to the lowest bounding estimate of BEIR II (absolute Risk-Plateau Model) (Ref. 12).

Under two of the five assumptions tested, the mining industry is found to have the highest index of harm; under a third assumption, it comes very close to registering the highest index. The true index of harm for the mining industry--and for most of the others--may be understated, in view of current controversies over the extent of occupationally induced diseases. Even so, mining appears to be the riskiest industry under all assumptions.

Judging from the rankings under all five assumptions, and using the reference ICRP dose/risk model, the industry occupational-risk leaders seem to be mining, AF&F, construction, transportation, and manufacturing, while the radiological "industry" at its current average dose level of around 0.35 rem/yr is among the least risky. The point of including results for a dose level at the exposure limit of 5.0 rem/yr is to show that even if such conditions existed, the radiological "industry" would still not be the riskiest if the ICRP estimate is valid. At that level of exposure, it is a clear leader where death from radiation is weighted most heavily; in the case of two other assumptions--weighting most heavily, in turn, genetic damage, and somatic damage to the fetuses and embryos of pregnant women--it is only slightly riskier than mining. However, we emphasize that the results at an average exposure dose of 5.0 rem/yr do not imply that any group is actually exposed to such a level over time. Exposure at that level is

Table 2. Indexes of Harm for Radiological and Nonradiological Industries Under Selected Assumptions

(Index of Harm, $I(X_{ij})$, by Weighting Assumption k)					
Index (i)	Industry	Radiation Damage to Fetuses and Embryos of Pregnant Women Perceived as Highest Risk			
		Equal Weighting (k=1)	Death Perceived as Highest Risk (k=3)	Death from Radiation Perceived as Highest Risk (k=4)	Genetic Damage Perceived as Highest Risk (k=5)
Nonradiological:					
1	AF&F	0.197	0.387	0.079	0.079
2	Mining	0.408	0.841	0.163	0.163
3	Construction	0.260	0.504	0.104	0.104
4	Transportation	0.188	0.343	0.075	0.075
5	Trade	0.054	0.077	0.022	0.022
6	Finance	0.020	0.035	0.008	0.008
7	Services	0.043	0.063	0.017	0.017
8	Manufacturing	0.080	0.099	0.032	0.032
9	Radiological (by dose in Rem/yr):*				
9a	5.0**	0.189	0.329	0.526	0.211
9b	0.5	0.019	0.033	0.053	0.021
9c	0.35	0.013	0.023	0.037	0.015
9d	0.25	0.009	0.016	0.026	0.011
9e	0.1	0.004	0.007	0.011	

*These reference cases represent ICRP estimates of nuclear fatality rates corresponding to lower bound BEIR II estimates.

**This represents a regulatory limit and is not indicative of general industry practice.

fictitious, because nowhere is an occupational group exposed to radiation at that level day after day or subjected to an average level that high.

The principal feature of both Table 2 and Fig. 5 is that the indexes of harm of the top five industries with respect to nonradiological harms are far more sensitive to the different assumptions than is the radiological "industry" at its current 0.35 rem/yr average exposure dose, referred to as the "low-risk" ICRP reference model.

Figure 6 shows the results from Table 2 under assumption $k = 1$ separately, with the ICRP dose/risk parameter multiplied by factors of 0.5 and 5.0 as proxies for optimistic and pessimistic views of the ICRP estimates. Instead of the discrete values we had before, we now show ranges of values that more appropriately reflect the uncertainty inherent in the ICRP data. Even at the highest point in its range, the index of harm at the 0.35 rem/yr exposure level still has a value lower than the indexes of five nonradiological industries. Precisely at what point in the range one feels comfortable making the comparison depends almost entirely, in the absence of empirical evidence, on both one's fear of cancer and other radiation-induced effects, and on the allowance one makes for delayed effects in formulating the index. Some researchers are asserting that the linear hypothesis is not conservative after all, and that the risks at low levels of radiation are much greater than linear extrapolations would indicate (Ref. 13). Others assert the opposite. Precisely how much greater or less is a question still to be answered.

CONCLUSIONS

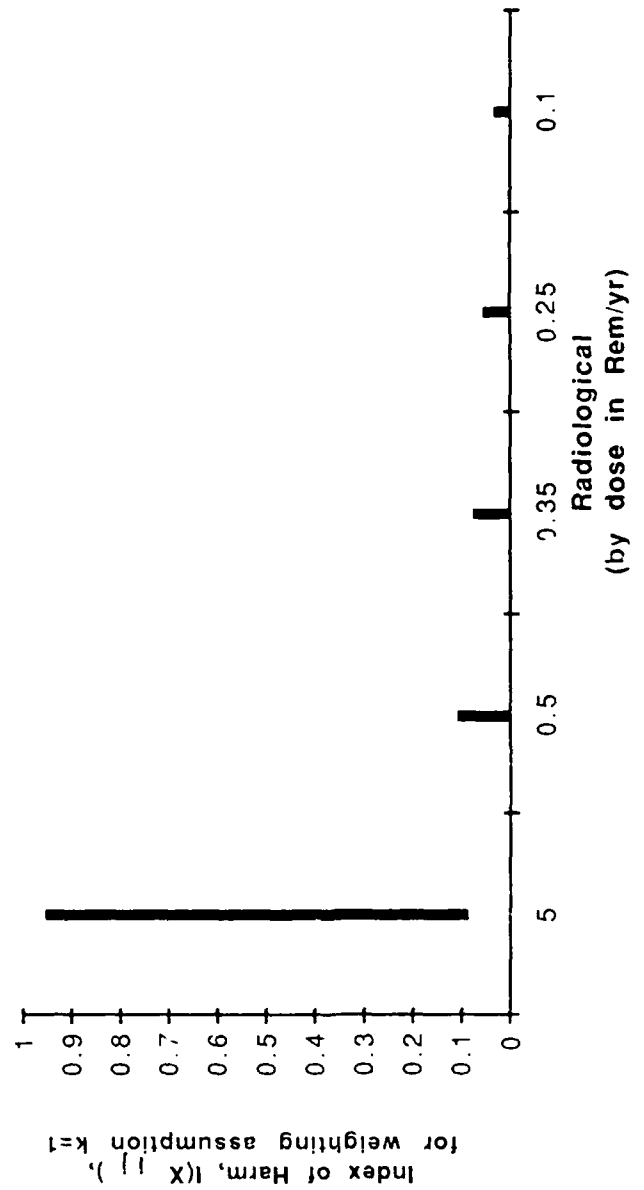
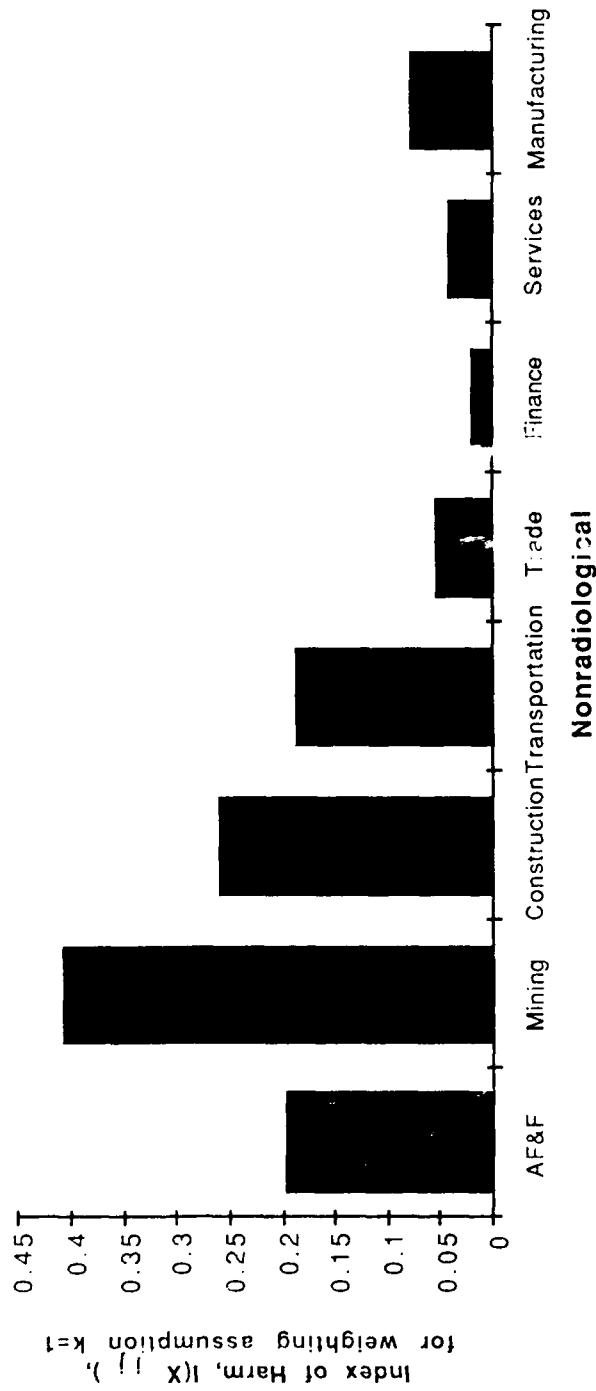
The index-of-harm methodology developed in this study has been applied to U.S. industry lost-year statistics with respect to nonradiological harms and to the ICRP/dose-response model for radiation-induced harms (workers exposed to the latter types of harm constitute a mere fraction of all occupational workers in the United States). Because of great uncertainty associated with the ICRP estimate, and its

Figure 5. Index-of-harm industry rankings for each of five assumptions
ICRP reference case: nuclear fatality rates corresponding to
the lowest risk model proposed in BEIR II



Source: Reference Table 2.

Figure 6. Indexes of harm for nonradiological industries compared with index-of-harm ranges for radiological industry by dose level, under equal weighting assumption



potential bias on the side of low radiological risk, we developed an appropriate range of indexes as proxies for optimistic and pessimistic views of those data.

The index was computed by summing the effect of a number of harms appropriate to the occupational environment of those industries and properly based on the subpopulation likely to experience those harms. Its principal virtue is that it can be compared across industries. Further, the weighting factor for valuing the harms has been included here as a variable, enabling us to vary it parametrically depending on the number, types, and perceived severity of the harms considered.

This last feature is at the same time the study's greatest strength and weakest point. The values we have ascribed to our various assumptions have been arbitrary, yet the issues are desperately important. Is death from radiation, for example, worse than death from other causes? Or is death the same by any name? Would we view with indifference the same number of days lost from accidental injury as from radiation-induced somatic effects? Is death from radiation more or less acceptable than the genetic damage radiation can cause? And how might one place a value on the life of an off-spring (of a first or subsequent generation) which may be either deformed, retarded, or otherwise damaged genetically? To the extent that questions such as these can be posed and data gathered to address them, our perception of risk will change and so will the process of setting industrial safety standards.

The limitations associated with the index of harm can best be appreciated by the variety of ways we could have derived it. For example, we could have based it on the entire radiological industry or just part of it; on all kinds of risk or just those from radiation; on a valuation of occupational risks either equal to or above those experienced by the general population; or on some absolute scale, or one relative to other natural risks. Depending on how those issues are handled and hence how risk is perceived, the values calculated for an index of harm will differ.

In the end, risk is perceived differently by different individuals, and what may be an acceptable risk for people in one industry may not be so viewed by those in another, even if the sizes of the two industries are roughly equal.

The index of harm developed in this paper can be a flexible and useful tool in risk analysis. It could be used in a number of potentially useful ways, three of which are:

- To compare the relative risk of occupational workers exposed to different kinds of harm (as in this paper); the index reduces to a common denominator the effects of harms that hitherto could not be compared. Moreover, using a parametric approach enables different perceptions and valuations of risk to be treated and evaluated.
- To evaluate the "benefit" side of a cost-benefit equation by using the index to estimate a particular strategy's potential for reducing occupational risk. Questions such as which harms should have their effects reduced and by how much (in addition to evaluating alternative means to accomplish such ends) could be analyzed in a broad way.
- To expand the formulation of the index to include both immediate and delayed effects of both radiological and nonradiological harms whenever appropriate data become available. Developing the methodology in this and other ways would yield a more precise and reliable indicator.

The principal finding of this study's interindustry comparison of risk is that at current levels of radiation exposure and based on the apparently low ICRP estimates of the dose-harm relationship, the radiological industry ranks among the less risky industries (note that the rankings change, however, when our more pessimistic risk estimates are used). It could thus be argued that a more cost-effective solution from society's standpoint would be to make the riskier industries safer. For example, it has been reported that radiological workers' latent

cancer risks are lower than an average worker's actual risk of fatal occupation accidents (Ref. 14, p. 6), and that the average actual risk to radiological workers is no higher than the average risk from fatal industrial diseases in nonradiological industries (Ref. 14, p. 5). Even if the ICRP estimates are regarded pessimistically and an index of harm five times as large as the 0.35 rem/yr average-dose level (Fig. 6) is assumed, the radiological industry is shown to be relatively safe. In light of the recent, and somewhat divided, findings of the BEIR (Ref. 15) presented in the recent BEIR III report, a factor of 5 appears to represent a reasonable approximation of the range of uncertainty. However, we have not considered the actual range of the BEIR III results explicitly in our work. Furthermore, as discussed earlier, the rankings are altered considerably at the regulatory dose level.

Overall, given more robust data and a more refined formulation of the index, we believe the methodology we have developed here may become a useful tool in analyzing and comparing occupational risks across industries. The next two sections together explore further work that needs to be done and the improvements possible in the index.

IV. AN ILLUSTRATIVE EXAMPLE

Although we strongly believe that the extensions to the index-of-harm methodology described in this paper are in the right direction and capable of addressing important questions, the chief factor limiting the index's usefulness now is inadequate data. But it is not the only factor. Certainly the index of harm-greatly simplified in this paper precisely because so little data were available-could doubtless be further refined as more is learned about the complex nature of risk and how to measure its various facets.

One way of showing how little is yet known about risk assessment and measurement is to apply the above analysis to a specific example. The one we have chosen was suggested in early 1978 when the Nuclear Regulatory Commission (NRC) first wished to open rulemaking proceedings and hold hearings on whether workers in nuclear facilities and, to a lesser extent, those in nonradiological industries, should be exposed to substantially less risk from radiation. The NRC was expected to consider a National Resources Defense Council motion to lower the maximum allowable occupational radiation dose tenfold from 5.0 to 0.5 rem/yr. This example, in exploring whether we have sufficient basis for lowering that limit, concludes that the actual quantification of the net risk reduction resulting from such a step cannot be made without more relevant estimates. Our index-of-harm analysis can provide some of those estimates.

The maximum allowable whole-body dose to which workers in radiological occupations are subject has been declining steadily over the last half century (Ref. 15, p. 146).

Period	Maximum allowable whole-body dose
	(rem/yr)
1931-36	60
1937-48	30
1949-57	15
1957-78	5

This historical trend may not continue as a matter of course; any further reduction in the maximum dose limit may have to be justified on grounds of risk-cost-benefit considerations. Yet, as we have seen, measuring radiological risk and assessing its relative severity are both difficult and subjective.

Despite the relatively low average-exposure dose of 0.35 rem/yr experienced by workers in the U.S. radiological industry as a whole, and the large number of relatively safe sites, lowering the allowable exposure dose across the board would still affect a few select workers at each site whose exposure is well above the average (such high individual doses are masked by the average-exposure figures for particular sites).¹ Lowering the standard therefore implies limiting the dosage of high-exposure workers with at least the following cost implications:

- Adopting any one of a number of retrofit strategies, including the use of new tools, designing new shielding, longer reactor cooldown periods before maintenance, and increasing maintenance efficiency.
- Hiring additional (and initially less experienced) personnel to share and thus reduce the individual radiation dose experienced by high-exposure workers. [It is believed that NRC licensees would prefer this apparently less costly solution to others in the event the allowable exposure dose were lowered (Ref. 14, p. 7).] Yet, if demand outstripped supply for such skilled workers, the costs could be much higher. On the other hand, if enough extra people are not hired, reaching the annual dose limit before the end of the year becomes a real possibility and could force the facility to shut down. It has been estimated that if the limit were reduced to 0.5 rem/yr, the cost to nuclear plant licensees alone for extra workers and extended plant outages during the years 1979 to 2000 could be between

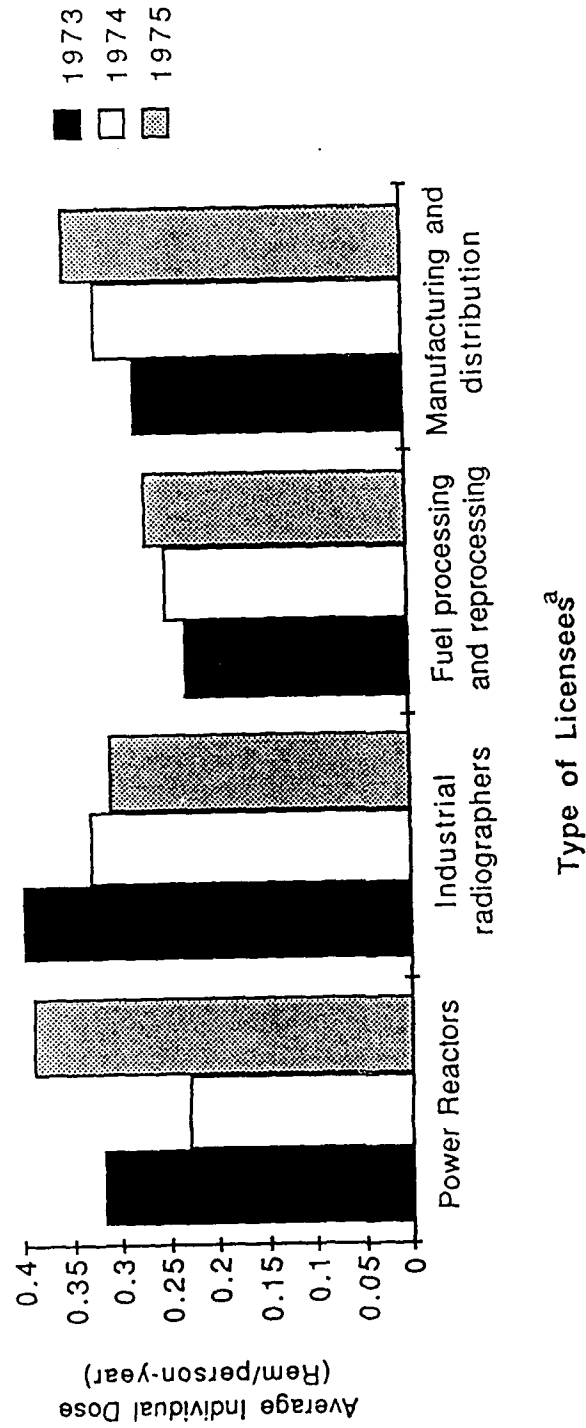
¹A radiologically hazardous site is defined as one whose workers are exposed to doses approaching 5.0 rem/yr.

\$23 billion and \$53 billion. (Ref. 14, p. 23, and Encl. F, p. 46).

- Increasing the potential for accidents and injury by using less experienced workers.
- Increasing the number of persons exposed to low-level radiation, and potentially the collective risk. The NRC staff believe that "any regulatory action aimed at reducing occupational radiation risks should also be directed at reduction in the collective dose." Figure 7 presents average individual and extrapolated collective doses by radiological industry licensee type. The overall risk of latent effects such as cancer appears to be associated with the number of person-rems received rather than the individual radiation dose. (Ref. 14, Encl. A, p. 1).
- Reducing efficiency by wasting large portions of skilled worker time, probably the largest hidden cost of lowering the allowable dose. One highly exposed worker might put in 6.4 hours of productive work in an eight-hour shift (80 percent efficiency), 1.6 hours being required for setup and maneuvering in and out of the workplace. For two workers to do the same work, thereby halving the exposure of each, their efficiency would also halve to 40 percent. In the process, each would be forced to waste 3.2 hours a shift (or at least might have to be trained to perform other, potentially less valuable work away from radiation zones).

All of the above consequences appear quite costly both in real terms and in further potential risk, so that it would seem appropriate and even desirable to assess the magnitude of these costs--and who would bear them--before lowering the exposure limit. Whereas most nuclear reactors and fuel-cycle facilities would require a few physical retrofits, some older facilities may need substantial and costly modifications. Even if it were found that the costs at certain facilities would appear prohibitive, the total financial effect of the change on the radiological industry may still be small enough to justify it.

Figure 7. Average individual collective doses for 10CFR licensees
1973-1975



Source: Reference 11

^a The four types of licensees have been reporting pursuant to 10CFR Part 20 requirements since 1973. Prior reports include only those estimated doses in excess of 1.25 rem/yr. Does not include medical applications or cosmic-radiation doses endured by airline pilots and frequent air travelers..

A judgment on the issue can be reached only by weighting the added costs incurred in the industry and who would bear them with the amount of risk reduction those expenditures could potentially buy.

Lowering the low-level exposure dose limit from 5.0 to 0.5 rem/yr means reducing the radiological industry average dose from about 0.35 to 0.25 rem/yr. Our index-of-harm analysis showed, for each of the five assumptions examined, the following estimated reductions in the index as a consequence:

Reduction in index of harm through lowering the exposure limit from 5.0 to 0.5 rem/yr ^a		
Assumption	Absolute	Percentage
(1) All harms weighted equally	0.004	31
(2) Radiation damage to fetus and embryo perceived as highest risk	0.003	25
(3) Death perceived as highest risk	0.007	30
(4) Death from radiation perceived as highest risk	0.011	30
(5) Genetic damage perceived as highest risk	0.004	27

^aBased on ICRP estimates shown in Table 6 and assuming that the industry average is reduced from 0.35 to 0.25 rem/yr (30 percent decrease).

The above figures show reductions in the index between 25 and 31 percent, and indicate broadly what the costs imposed on NRC licensees due to lowering the exposure dose limit (whatever those costs are) will buy in terms of risk reduction. Because of the assumed linearity of the dose-response mode, this approximately 30 percent reduction would be insensitive to the risk parameters. It is conceivable to imagine a somewhat more highly developed index being used in this way to provide an estimate of potential "benefits" from either a regulatory action or the implementation of some risk-reducing strategy. Hopefully, decisions in

this area will be based more on rational cost-benefit analysis than on purely political or emotional grounds. A methodology that can treat subjective judgment explicitly and quantitatively—even parametrically as in this paper—is a step in that direction, although by itself may be insufficient as a policy tool. Other factors, often unquantifiable, may play more decisive roles.

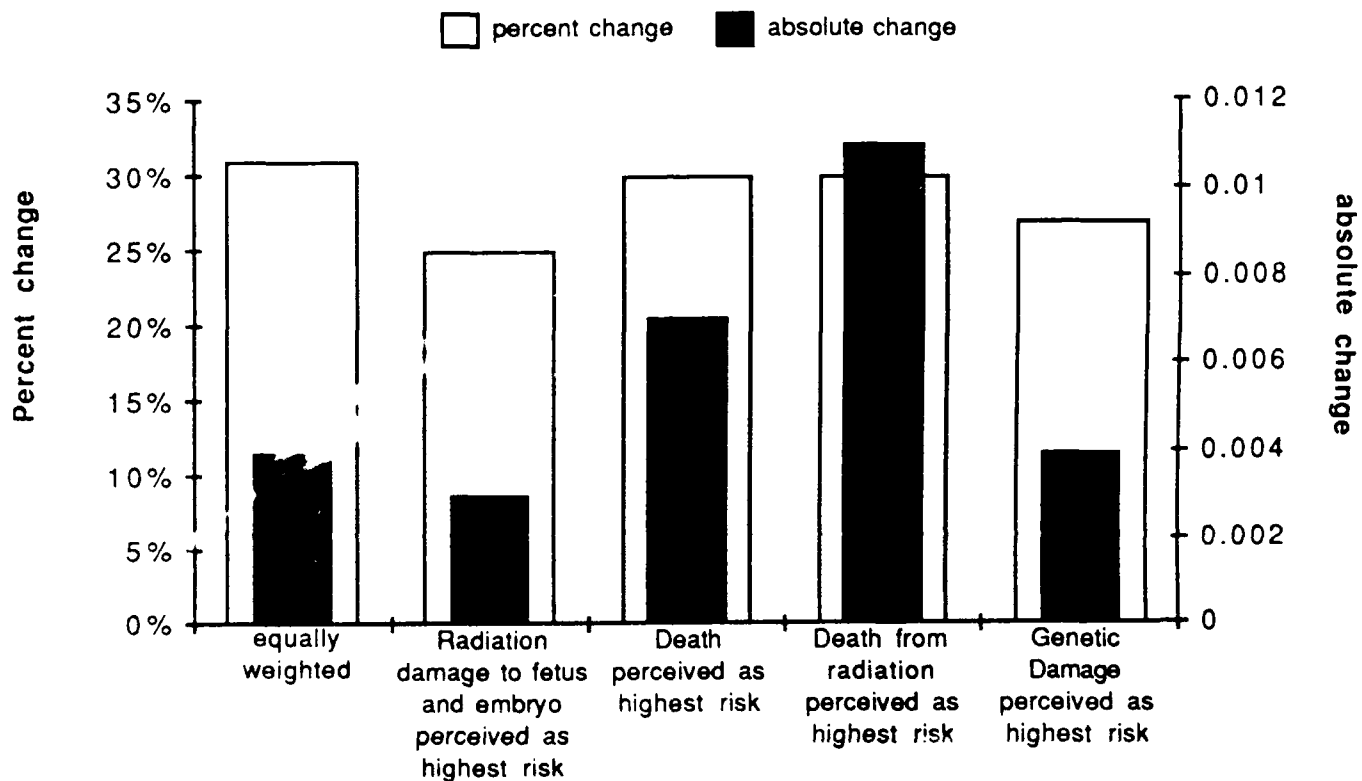
Whereas reducing the limit across the board may be a convenient measure, it overlooks the complicated nature of risk. The index of harm, although allowing the relative risks of injury, illness, and death to be compared across different industry sectors, nevertheless remains a subjective measure whose usefulness depends critically on how the various harms are valued. Occupational harms, even ones with equivalent effects, are seldom valued equally. Moreover, some kinds of harm, to which certain groups are more susceptible, are riskier overall than others. What these statements suggest is that the nature and extent of the harm, as well as who is harmed, are major determinants of the risk involved and also affect how the risk is perceived.

While blanket regulations may be convenient to enforce, it is difficult to assure that they also are equitable. Since the safety of all radiological workers is important, we suggest that additional attention focus particularly on those who receive higher-than-average doses or those most susceptible to radiation-induced damage. Accordingly, a number of alternative policies merit consideration and further detailed investigation:

- Protect women of childbearing age—especially pregnant women—from receiving any occupational radiation exposure. The risk of dying prematurely from cancer is greater for younger than older people, and greater for women than men at all age levels (see Fig. 8). Such a policy would also protect this group from the potential genetic effects of radiation.²

²An interesting civil rights and civil liberties issue emerged about 10 years ago and posed medical, legal, economic, and moral dilemmas. "The issue involves, first of all, the right of fertile women to hold jobs and not suffer discrimination. It also involves the even

Figure 8. Reduction in index of harm through lowering the exposure limit from 5.0 to 0.5 rem/yr ^a



^a Based on ICRP estimates shown in Table 2, and assuming that the industry average is reduced from 0.35 to 0.25 rem/yr (~30% decrease).

- Reduce the allowable dose for young people of both sexes, say under 25 years of age, as this group is most likely, if affected by radiation, to transmit genetic damage to their offspring. Because of the long latency period, its members also possess the highest risk of dying prematurely from cancer.
- Reduce the allowable exposure dose, possibly by an amount less than a factor of 10 (to lessen what might otherwise be prohibitive costs) and apply the new standard only to those in the radiological "industry" currently exposed to doses higher than that standard. In addition, to guard against a rising

larger, more emotional and more portentous issue of the threat to the reproductive capacity and genetic stability of hundreds of thousands of men and women whose jobs expose them to substances that can cause sterility or cause mental or physical deformity in fetuses" (Ref. 16, p. A1). The issue appears just when women are entering industrial jobs in significantly larger numbers as a result of their struggles against job discrimination. They are now seemingly confronted, in certain jobs, "with the dismal choice of relinquishing their right to have children or their jobs" (Ref. 17).

This issue is not clear-cut. Employer's intentions of protecting such women and their fetuses are being openly challenged on scientific grounds. For a variety of hazardous substances, a "safe" level of exposure cannot be determined because the data are inadequate, even though the National Institute for Occupational Safety and Health (NIOSH) now distinguishes between 56 mutagens—substances that can damage or change genetic structures—and 471 teratogens—substances that can create physical or mental deformities (Ref. 16, p. D8). Rather than prohibit women of childbearing age from holding certain hazardous jobs—the most economical alternative open to an employer—a number of agencies including Occupational Safety and Health Administration insist that the solution should be to make the workplace safe for workers (Ref. 16, p. D8).

A 1977 survey to determine the extent of sex discrimination among female industrial radiation workers concluded that "women of child-bearing age are discriminated against" (Ref. 18). However, the sample was small: of 143 women who received the survey, 59 completed it, and 30 of those were or had been employed as radiation workers. Furthermore, only "four or five" respondents. . . either had been restricted—or knew of instances where other workers had been restricted—by radiation exposure limits more stringent than those applied to their male colleagues." Nevertheless, the study draws attention to a potentially embarrassing problem, particularly in view of NRC Regulatory Guide 8.13, which recommends that "a woman who is pregnant receive not more than 0.5 rem during pregnancy" compared with the 5.0 rem/yr radiation limit for all occupational adults.

collective risk, limits should be set appropriate to the size of licensee in total person-rem/yr terms.³

³It has been estimated that additional workers in the nuclear reactor sector would cause increases in the collective dose of between 20 and 450 percent (Ref. 14, Enclosure A, p. 9). And one collective-dose standard across the industry would penalize the larger licensee organizations unfairly and severely disrupt their operations (Ref. 14, Enclosure A, p. 25).

V. TOPICS FOR FURTHER RESEARCH

The illustrative example in Sec. IV showed clearly the extent to which we are unable to resolve pressing issues for want of adequate data. Just in that one area, the following topics need investigating:

- A comprehensive assessment of the full costs of specific reductions in the allowable exposure limit and who would bear them. (Major cost categories include retrofit equipment, additional workers, decreased worker productivity, potentially increased collective radiation dose and risk of accidental injury, and increased risk of outages and licensee downtime.)
- The extent to which the alternative policies suggested, or others, reduce overall risk to both occupational workers and the general population compared with an across-the-board reduction in the allowable exposure limit. Which policy would be most cost-effective?
- The development of more precise estimates of radiological risk in the nuclear-reactor industry.¹
- An assessment of the regulatory and legislative implications of reducing radiological exposure limits for select groups, specifically women of childbearing age. What are the specific tradeoffs between civil liberties and job rights on the one hand and costs (both to obtain more data and to comply with possibly stricter laws) and potential inflationary effects on the other?

In order to develop the methodology further to give both industry and government a more robust indicator, we would suggest further research in the following areas:

¹The NRC staff believe this risk is underestimated (Ref. 14, Enclosure B, p. 4). The nuclear-risk estimates used in this paper are derived from theoretical projections, whereas the risks inherent in the nonradiological industries are based on empirical data.

- Determine how the index of harm varies among both workers and sectors within each industry. Data for nonradiological industries are average figures that mask extreme intraindustry variations. For example, in construction, building a 90-story tower entails larger risks than building a warehouse. Including intraindustry variations may alter the way the index is formulated.
- Explore alternate ways of measuring the harm to and reducing risk for both occupational workers and the general population. Such an analysis would either strengthen the way the present index is formulated or would provide strong arguments for changing it. Candidate alternatives for measuring the effects of occupational harm include: by industry on a societal basis; by fuel cycle on an individual basis; or by nature of risk (as in this study).
- Perform surveys among both occupational workers in various industries and the population at large, first to elicit different ways in which various harms can be valued, and then to see whether patterns exist in the way various groups value them. The assumptions treated parametrically in this study were arbitrary and merely illustrative; substituting more realistic data would yield valuable information and possibly also change the formulation of the index.
- Collect statistics by industry grouping on average ages at death. By comparing these data with general U.S. mortality data less immediate deaths accounted for, we could develop needed statistics for delayed mortality. Such data would help to adjust upward the data used in Figures 2A, 2B, and 2C, which underestimate the effects of the nonradiological harms by considering only immediate and not delayed effects.
- Compare the costs of alternative strategies to reduce risk, taking into account the nature of the risk, the populations affected, and the time frame over which the strategy could be implemented.

VI. REFERENCES

1. ICRP Publication 27, London: Pergamon Press, "Problems Involved in Developing an Index of Harm," *Annals of the International Commission on Radiological Protection*, May 1977.
2. "Occupational Injuries and Illnesses in Industry," U.S. Department of Labor, Washington, D.C., Bulletin, 1982, 1984.
3. "Occupational Injuries and Illnesses in Industry," U.S. Department of Labor, Washington, D.C., Bulletin, 1983, 1985.
4. "Occupational Injuries and Illnesses in Industry," U.S. Department of Labor, Washington, D.C., Bulletin, 1984, 1986.
5. "Occupational Injuries and Illnesses in Industry," U.S. Department of Labor, Washington, D.C., Bulletin, 1985, 1987.
6. Solomon, K. A., "Issues and Problems in Inferring a Level of Acceptable Risk," The RAND Corporation, R-2561-DOE, July 1980 (coauthored).
7. Solomon, K. A. and S. C. Abraham, "The Index of Harm," *Health Physics*, Vol. 38, March 1980, pp. 375-391.
8. "California Work Injuries," Division of Labor Statistics, Sacramento, California, 1972, 1980.
9. "California Work Injuries," Division of Labor Statistics, Sacramento, California, 1972, 1981.
10. "California Work Injuries," Division of Labor Statistics, Sacramento, California, 1974, 1982.
11. "Health and Work in America," APHA Chart Book, presented at the 103rd Annual Meeting of the American Public Health Association in Chicago, November 1975, 16-20.
12. "The Effects on Population of Exposure to Low Levels of Ionizing Radiation," Committee on Biological Effects of Ionizing Radiation (BEIR), National Academy of Sciences, National Research Council, Washington, D.C., 1972.
13. Marx, J. L., "Low-Level Radiation: Just How Bad Is It?," *Science* 204, 1979, 160-164.

14. Minogue, R. B., "Further Actions to Control Risks Associated with Occupational Radiation Exposures in NRC-Licensed Activities," paper SECY-78-415 prepared for the Commissioners of the U.S. Nuclear Regulatory Commission, July 31, 1978.
15. Becker, F. B., "Cancer," New York: Plenum Press, Vol. 1., 1977.
16. Shabecoff, P., "Job Threats to Workers' Fertility Emerging as Civil Liberties Issue," *New York Times*, 15 January, 1979, pp. A1, D8.
17. Richards, B., "Five Women Say They Were Pressured into Sterilizations to Keep Chemical Plant Jobs," *Los Angeles Times*, 2 January, 1979, Part I, p. 5.
18. "Study Finds Discrimination Against Radiation Workers," *Nuclear News* 21(14), 1978, 162-166.